

Search for Outer Massive Bodies around Transiting Planetary Systems: Candidates of Faint Stellar Companions around HAT-P-7*

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Abstract

We present results of direct imaging observations for HAT-P-7 taken with the Subaru HiCIAO and the Calar Alto AstraLux. Since the close-in transiting planet HAT-P-7b was reported to have a highly tilted orbit, massive bodies such as giant planets, brown dwarfs, or a binary star are expected to exist in the outer region of this system. We show that there are indeed two candidates for distant faint stellar companions around HAT-P-7. We discuss possible roles played by such companions on the orbital evolution of HAT-P-7b. We conclude that as there is a third body in the system as reported by Winn et al. (2009, ApJL, 763, L99), the Kozai migration is less likely while planet-planet scattering is possible.

Key words: stars: planetary systems: individual (HAT-P-7) — stars: binaries: general — techniques: high angular resolution

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

1. Introduction

The discovery of over 400 extrasolar planets and the diversity of their orbital distributions dramatically changed our perception of planetary systems in the last 15 years. Especially, the existence of exoplanets in very close-in

or eccentric orbits stimulated theorists to develop various models for planetary migration during the epoch of planet formation. To explain the orbital distribution of known exoplanets, a number of planetary migration models have been proposed, including disk-planet interaction models (i.e., Type I and Type II migration models; e.g., Lin & Papaloizou 1985; Lin et al. 1996; D’Angelo et al. 2002; Ida & Lin 2004), planet-planet scattering models considering gravitational interaction among multiple giant planets (i.e., jumping Jupiter models; e.g., Rasio & Ford 1996; Marzari & Weidenschilling 2002; Nagasawa et al. 2008; Chatterjee et al. 2008), or Kozai migration models considering perturbation by a distant massive companion and coinstantaneous tidal evolution (e.g., Wu & Murray 2003; Takeda & Rasio 2005; Fabrycky & Tremaine 2007; Wu et al. 2007).

These planetary migration models can now be tested by observations of the Rossiter-McLaughlin effect (hereafter the RM effect: Rossiter 1924; McLaughlin 1924) for transiting planetary systems, which is an anomalous shift in observed radial velocities due to the occultation of a rotating star. Measurements of the RM effect enable us to estimate the sky projection angle of the planetary orbital axis relative to the stellar spin axis (i.e., the spin-orbit alignment angle; Ohta et al. 2005; Gaudi & Winn 2007; Hirano et al. 2010). The information of the spin-orbit alignment angle is very useful to differentiate the planet-planet scattering models and the Kozai migration models from the disk-planet interaction models, because the former models predict a wider range of spin-orbit alignment angles for migrated planets, while the latter models predict that migrated planets would have only small spin-orbit alignment angles. Thus an observation of a highly tilted orbit for a specific planet is strong evidence of a planet-planet scattering process or perturbation by an outer companion during its migration history.

Indeed, very recently several transiting exoplanets have been reported to show such highly tilted orbits via measurements of the RM effect. These observations lead to an interesting prediction: around these spin-orbit misaligned exoplanets, other massive bodies (e.g., massive planets, brown dwarfs, or a low-mass stellar companion) should be present. In addition, since migration mechanisms for such exoplanets cannot be distinguished by the spin-orbit alignment angles alone, direct imaging of such massive bodies gives us important additional information to distinguish between the two migration mechanisms of highly tilted orbit planets. Motivated by these facts, we have initiated to search for such outer massive bodies around known transiting planetary systems with the Subaru HiCIAO (High Contrast Instrument for the Subaru next generation Adaptive Optics; Tamura et al. 2006; Hodapp et al. 2008; Suzuki et al. 2010, in prep.), as part of the SEEDS project (Strategic Explorations of Exoplanets and Disks with Subaru, PI: Motohide Tamura). The Subaru HiCIAO is a powerful instrument to search for outer faint bodies around stars, proven by the detection of a massive planet or a brown dwarf around GJ 758 (Thalmann et al. 2009).

Table 1. Summary of stellar and planetary parameters.

Parameter	Value	Error	Source
Star			
M_s [M_\odot]	1.520	0.036	CKB10
R_s [R_\odot]	1.991	0.018	CKB10
Age [Gyr]	2.14	0.26	CKB10
Distance [pc]	320	$^{+50}_{-40}$	PBT08
app. H mag.	9.344	0.029	Cutri et al. (2003)
Planet			
M_p [M_{Jup}]	1.82	0.03	WOS10
R_p [R_{Jup}]	1.50	0.02	WOS10
i [$^\circ$]	83.1	0.5	WOS10
a [AU]	0.0386	0.0001	WOS10
P [days]	2.204733	0.000010	WOS10

In this paper, we targeted the transiting planetary system HAT-P-7, which was reported to have a planet (HAT-P-7b) on an orbit highly inclined relative to the stellar equatorial plane (Narita et al. 2009; hereafter NSH09, Winn et al. 2009; hereafter WJA09). Consequently, we report two candidates of faint stellar companions to HAT-P-7 based on the Subaru HiCIAO and the Calar Alto AstraLux data. Although our data alone cannot distinguish whether or not the candidate companion stars are physically associated with HAT-P-7 at this point, the findings are useful to constrain the mechanism of planetary migration in this system. We summarize the properties of our target in section 2, and report our observations, analyses, and results in section 3. We present theoretical discussions of the migration mechanism of HAT-P-7b in section 4. Finally, section 5 summarizes the findings in this paper.

2. Target Properties

HAT-P-7 (also known as Kepler-2) is an F8¹ star, hosting a very hot Jupiter HAT-P-7b (Pál et al. 2008; hereafter PBT08). The stellar distance was estimated as 320^{+50}_{-40} pc (PBT08). According to 2MASS catalog (Cutri et al. 2003), the H band magnitude of HAT-P-7 is 9.344 ± 0.029 . This star is in the field of view of the NASA Kepler mission (Borucki et al. 2009), and detailed stellar parameters were reported through a Kepler asteroseismology study as follows; the mass $M_s = 1.520 \pm 0.036 M_\odot$, the radius $R_s = 1.991 \pm 0.018 R_\odot$, and the age 2.14 ± 0.26 Gyr (Christensen-Dalsgaard et al. 2010; hereafter CKB10). The planet HAT-P-7b has a very close-in orbit with the orbital period of 2.204733 ± 0.000010 days and the semi-major axis of $a = 0.0386 \pm 0.0001$ AU (Welsh et al. 2010; hereafter WOS10). The mass, radius, and orbital inclina-

¹ There is a slight uncertainty in the spectral subclass of HAT-P-7, and the uncertainty would have a slight effect on apparent i' and z' band magnitudes quoted in table 2. However, subsequent discussions and conclusion of this paper would remain unchanged.

tion of HAT-P-7b are $1.82 \pm 0.03 M_{Jup}$, $1.50 \pm 0.02 R_{Jup}$, and $83.1^\circ \pm 0.5^\circ$, respectively (WOS10). These properties are summarized in table 1.

The orbit of HAT-P-7b does not have a significant eccentricity (PBT08, NSH09, WJA09, WOS10). Nevertheless, NSH09 and WJA09 found that the planet has an extremely tilted orbit relative to the stellar rotation axis. In addition, WJA09 reported an additional long term RV trend, implying a third body in the planetary system. Thus this system is a very fascinating target of direct imaging to search for outer massive bodies.

3. Analyses

3.1. Subaru / HiCIAO

We first observed HAT-P-7 in the H band with the HiCIAO combined with the AO188 (188-element curvature sensor adaptive optics system; Hayano et al. 2008), mounted on the 8.2 m Subaru Telescope on UT 2009 August 6. The field of view was 20×20 arcsec, and typical natural seeing was about 0.5 arcsec on that night. We used the target star itself as natural guiding for AO188. We took 30 object frames with 19.50 s exposures (i.e., total exposure time was 9.75 min). The observations were conducted in pupil tracking mode to use the angular differential imaging (ADI: Marois et al. 2006) technique. The gain of the detector was $1.66 e^-$ per ADU, readout noise was $15 e^-$, and zero point magnitude (the magnitude of an object that would yield 1 ADU per s) of the image was $H = 24.654 \pm 0.036$ mag. Our Subaru HiCIAO reduction procedures were as follows. We first removed a characteristic stripe bias pattern arising from the Subaru HiCIAO detector. Then flat fielding was done using dome flat frames, and bad/hot pixels were removed. Note that we did not subtract dark frames since dark current of Subaru HiCIAO is sufficiently low for the exposure time. We corrected distortion of the field of view by comparison of an M15 image taken by Subaru HiCIAO on UT 2009 August 5 with that taken by HST/ACS. The measured pixel scale of Subaru HiCIAO was 9.44 ± 0.10 mas per pixel. We shifted frames to match stellar centroid and used the ADI technique to combine the object frames. Field rotation during our exposures was $7.023^\circ \pm 0.007^\circ$.

The median combined object frame is shown in the left panel of figure 1 (north is up and east is left, and the field of view is 12×12 arcsec, as a subset of the full 20×20 arcsec frame). Two faint sources at about 3 arcsec away were clearly detected. The FWHM of the PSF was 6.1 pixel (0.058 arcsec). We determined positions of the candidate companion stars using the *imexam* task in IRAF² and conducted aperture photometry using the *phot* task. We used the photometric standard star FS151 ($H = 11.946 \pm 0.008$ mag) to determine apparent H band magnitudes of the candidate companion stars, since HAT-P-7 in the image

was saturated. The apparent H band magnitude, separation angle, and position angle of each companion star from HAT-P-7 are listed in the left column of table 2. Combining our result for the separation angle and the PBT08 result for the stellar distance, we estimate that projected separation distances of these candidate companion stars from HAT-P-7 are about 1000 AU.

In addition, we used the locally optimized combination of images algorithm (LOCI, Lafrenière et al. 2007) to maximize the efficiency of the ADI technique and to search for fainter objects in the inner region around HAT-P-7. The upper right panel of figure 1 shows the LOCI reduced image around HAT-P-7 (north is up and east is left, and the field of view is 6×6 arcsec centered on HAT-P-7, as a subset of the full 20×20 arcsec frame). Clearly, the bright halo in the inner region seen in the left panel is significantly suppressed. The upper panel of figure 2 plots 5σ contrast ratio around HAT-P-7 achieved by the Subaru HiCIAO observation, and the lower panel of figure 2 shows corresponding detectable mass of companions, assuming the age of 2.14 Gyr and the COND model by Baraffe et al. (2003). We achieved post-LOCI 5σ contrast sensitivity for H band of $\sim 7 \times 10^{-4}$ at 0.3 arcsec, $\sim 2 \times 10^{-4}$ at 0.5 arcsec, and $\sim 6 \times 10^{-5}$ at 1.0 arcsec, corresponding to $\sim 110 M_{Jup}$, $\sim 80 M_{Jup}$, and $\sim 70 M_{Jup}$ companions, respectively. As a result, we exclude the presence of a stellar companion (more massive than $80 M_{Jup}$ within the 6×6 arcsec field of view) separated 0.5 arcsec or farther at the 5σ level. At this point, we have not yet put a stringent constraint on inner massive bodies. For instance, an M star ($\sim 100 M_{Jup}$) is not ruled out within 0.3 arcsec (~ 100 AU).

3.2. Calar Alto / AstraLux Norte Lucky Imaging

HAT-P-7 was observed in SDSS i' and z' filter with the AstraLux Norte Lucky Imaging camera (Hormuth et al. 2008) at the 2.2 m telescope at Calar Alto on UT 2009 October 30. The observations were part of a large-scale high resolution imaging search for close stellar companions to all known exoplanet hosts brighter than $i' = 16$ mag (see Daemgen et al. 2009 for the first results). The survey employs the Lucky Imaging technique, which provides almost diffraction limited images by shift-and-add drizzle combination of only the best few percent of a series of ~ 10000 very short exposures (~ 10 ms), selected by the Strehl ratio. For the photometric analysis of HAT-P-7 and its companion candidates, the best 10% of a total 20000 integrations of 15 ms exposure time were used, yielding a total integration time of 30 s. The combined z' band image is presented in the lower right panel of figure 1 (north is up and east is left, and the field of view is 12×12 arcsec).

The IRAF *phot* task was used for relative aperture photometry of HAT-P-7 and the eastern candidate companion. The western companion could not be seen in the AstraLux images. Combining the relative photometry with the JHK magnitudes of HAT-P-7 (Cutri et al. 2003) and the absolute magnitudes of an F8 main sequence star (Kraus & Hillenbrand 2007), we derive the apparent i'

² The Image Reduction and Analysis Facility (IRAF) is distributed by the U.S. National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

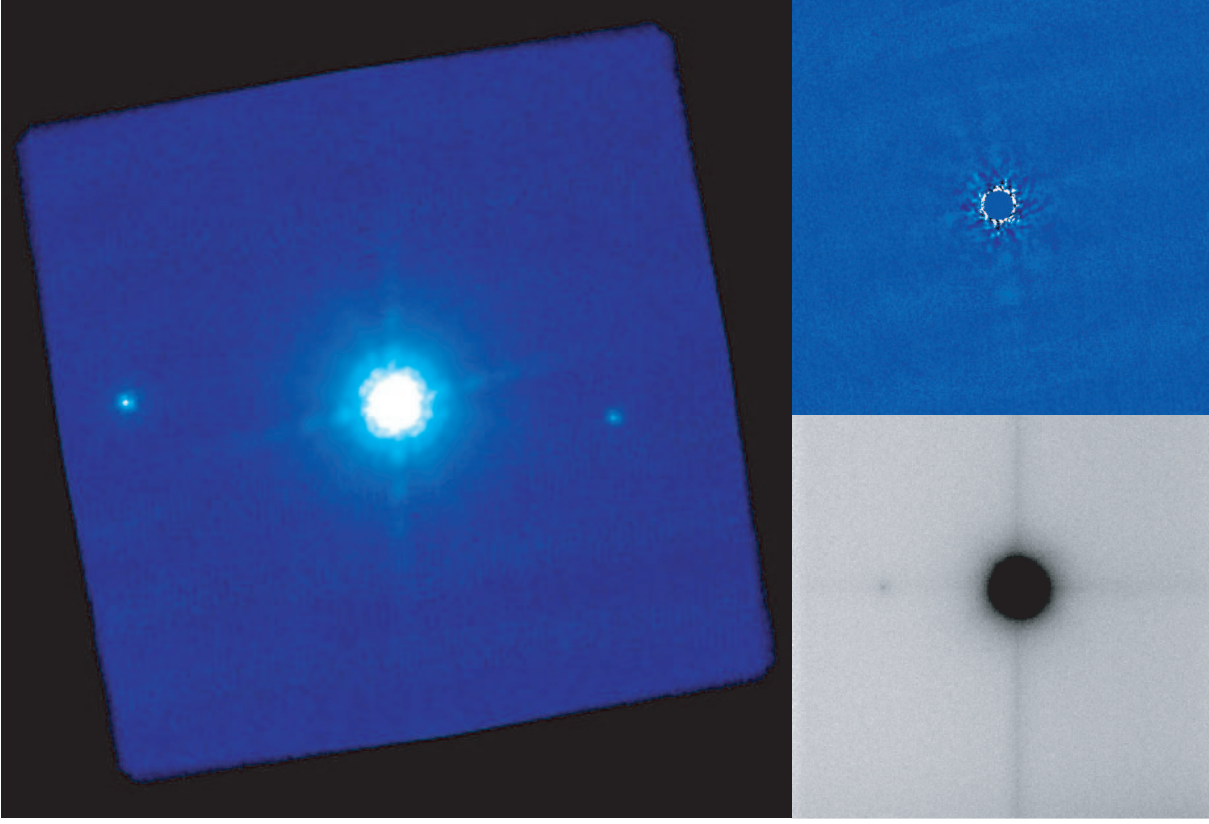


Fig. 1. Left: A median combined ADI image of HAT-P-7 in H band taken with the Subaru HiCIAO on UT 2009 August 6. The field of view is 12×12 arcsec. Upper right: A ADI/LOCI reduced Subaru image of the inner region around HAT-P-7. The field of view is 6×6 arcsec. Lower right: AstraLux z' band image of HAT-P-7 and the eastern companion candidate. The field of view is 12×12 arcsec. North is up and east is left for all panels.

Table 2. Magnitudes, positions, estimated[†] spectral type and masses of candidate companion stars.

Parameter	HiCIAO (H)		AstraLux (i') [‡]		AstraLux (z') [‡]	
	2009 August 6		2009 October 30		2009 October 30	
	Value	Error	Value	Error	Value	Error
West (fainter)						
apparent magnitude [mag]	16.92	0.06	>18.65	–	>18.55	–
separation angle ["]	3.14	0.01	–	–	–	–
position angle [°]	266.30	0.37	–	–	–	–
Estimated Spectral Type and Mass [M_{\odot}]	M9V-L0V (0.078-0.088)					
East (brighter)						
apparent magnitude [mag]	15.12	0.04	18.50	0.21	17.43	0.09
separation angle ["]	3.88	0.01	–	–	3.82	0.01
position angle [°]	89.81	0.30	–	–	90.39	0.11
Estimated Spectral Type and Mass [M_{\odot}]	M5V-M6V (0.17-0.20)					

[†]Assuming that the candidate companions are main sequence stars and at the same distance as HAT-P-7.

[‡]Assuming that HAT-P-7 is an F8 star.

and z' band magnitudes as $i' = 18.50 \pm 0.21$ mag and $z' = 17.43 \pm 0.09$ mag for the eastern companion candidate and upper limits of $i' > 18.65$ mag and $z' > 18.55$ mag for the western companion candidate. The astrometric calibration was achieved following the procedures outlined by Köhler et al. (2008) based on observations of stars with well defined astrometry in the Orion Nebula

Cluster. The derived image scale of AstraLux Norte for this observing run was 23.43 ± 0.06 mas per pixel. For the eastern companion candidate, we determined a separation of 3.82 ± 0.01 arcsec and a position angle of 90.39 ± 0.11 deg. These results are summarized in table 2.

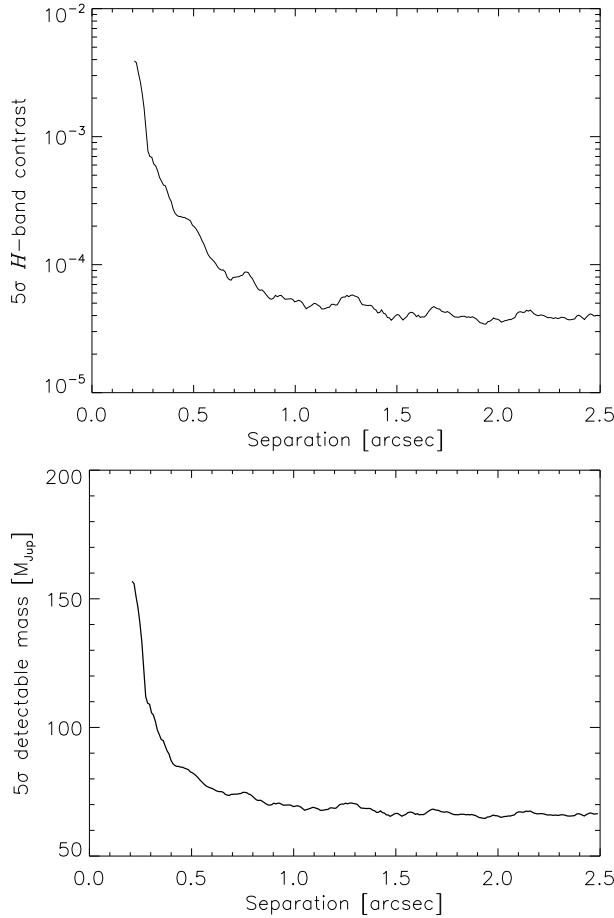


Fig. 2. Upper: ADI/LOCI 5σ contrast ratio around HAT-P-7 achieved by the Subaru HiCIAO. Lower: Corresponding constraint on detectable mass of companions, assuming the age of 2.14 Gyr and the COND model by Baraffe et al. (2003). We achieved the contrast ratio of $\sim 7 \times 10^{-4}$ (0.3 arcsec), $\sim 2 \times 10^{-4}$ (0.5 arcsec), and $\sim 6 \times 10^{-5}$ (1.0 arcsec), corresponding to the detectable mass of $\sim 110 M_{Jup}$, $\sim 80 M_{Jup}$, and $\sim 70 M_{Jup}$, respectively.

3.3. Combined Results

We discovered two candidates of faint stellar companions around HAT-P-7. As for the eastern companion, the i' - z' colors for the eastern companion suggest a main sequence spectral type of M5V-M6V, corresponding to 0.17 - $0.20 M_{\odot}$ (Kraus & Hillenbrand 2007; Covey et al. 2007). For this luminosity class, its apparent brightness in z' band yields as distance modulus of 10.03 mag for spectral type M6V, corresponding to a distance of ~ 300 pc. It is in agreement with the distance estimate for HAT-P-7 of 320^{+50}_{-40} pc (Pál et al. 2008). We note that the magnitude and color of the companion candidate would also be explained by a background M5III-M6III star at the distance of 126 kpc or more (Covey et al. 2007). As for the western companion, the AstraLux Norte observations only provide an upper limit on the i' and z' band brightness; we can just derive a lower limit on its i' - H and z' - H colors. Assuming that the western companion candidate is a main sequence star associated with HAT-P-7, its H band

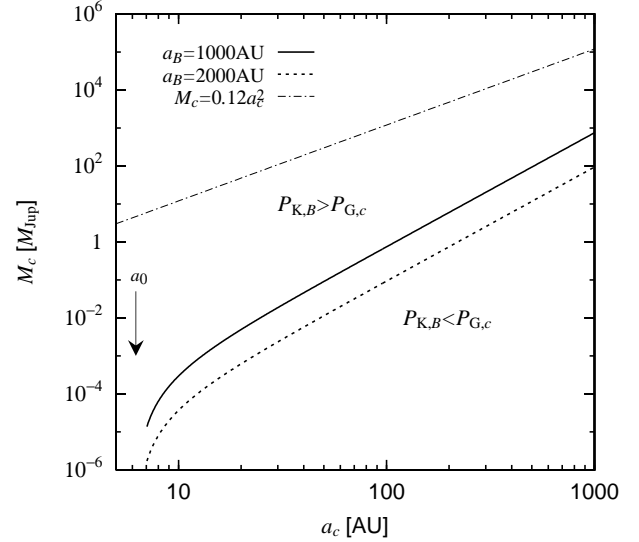


Fig. 3. Boundaries of the restricted area where HAT-P-7c cannot exist initially, since the timescale of orbital precession of HAT-P-7b caused by gravitational perturbation from HAT-P-7c ($P_{G,c}$) is shorter than that caused by the Kozai mechanism due to the distant companion ($P_{K,B}$). The solid line is for $a_B = 1000$ AU and the dotted line is for $a_B = 2000$ AU. The dashed-dotted line indicates a relation for the semi-major axis and the mass of HAT-P-7c reported by Winn et al. (2009). a_0 indicates a roughly estimated position of the snow line.

magnitude suggest M9V-L0V, corresponding to a mass in the range 0.078 - $0.088 M_{\odot}$ (see Kraus & Hillenbrand 2007).

We note that, however, it is unrealistic that both stars are true companions of HAT-P-7, because such a wide separation triple system is likely to be physically unstable and it is known that triple or quadruple stars discovered so far are hierarchial (Duquennoy & Mayor 1991). High spectral resolution observations for the candidate companion stars would be useful to constrain their peculiar radial velocities and thereby to discriminate their binarity. In addition, follow-up direct imaging observations, in the near future, will allow us to show via common proper motion whether the objects are true companions of HAT-P-7, whose proper motion is 18.60 ± 3.25 mas per year in the TYCHO reference catalogue (Hog et al. 1998). We note, however, that there are over 3σ inconsistency between the Subaru HiCIAO result and the Calar Alto AstraLux result (epoch difference of less than 3 months) for the separation angle of the eastern companion. However, at this point we do not conclude that the eastern companion is not associated with HAT-P-7, because the separation angle might be affected by the errors of the pixel scale, and also because the errors of the separation angle might be underestimated due to systematic errors caused by saturation or non-gaussian PSF shape. Thus further follow-up observations would be needed to distinguish whether the two stars are truly associated with HAT-P-7 or not.

4. Discussion

In this section, we discuss realizable migration mechanisms of the highly tilted orbit planet HAT-P-7b. First of all, as a simple case, if neither of the candidate companions we discovered is physically associated with HAT-P-7, only planet-planet scattering can explain the tilted orbit of HAT-P-7b. We thus examine a Kozai migration scenario for HAT-P-7b first, based on an assumption that either of the candidate companion stars is a true binary of HAT-P-7. We present conditions required for the Kozai migration of HAT-P-7b with a binary companion in section 4.1. We show a restricted area of a third body for the Kozai migration in this system in section 4.2., and describe the impact of the possible third body (HAT-P-7c) reported by WJA09 in section 4.3.

4.1. Required Condition for the Kozai Migration of HAT-P-7b

According to Kozai (1962), the angular momentum

$$L_Z \equiv \sqrt{G(M_p + M_s)a(1 - e^2)} \cos \Psi_m \quad (1)$$

should be conserved in a planetary system with a binary star during the Kozai mechanism, where G is the gravitational constant, M_p and M_s are the mass of the planet and its host star, a and e are the semi-major axis and the orbital eccentricity of the planet, and finally Ψ_m (domain: $[0^\circ, 180^\circ]$) is the mutual inclination between the orbital inclination of the planet and the binary star. In addition, given that the angular momentum is also conserved during tidal orbital evolution, $a(1 - e^2) \cos^2 \Psi_m$ should be conserved through the Kozai migration.

Using the conservation relation above, we constrain the initial mutual inclination to initiate the Kozai migration in this system as follows. First we assume that HAT-P-7b was born in the snow line with the initial eccentricity e_0 and the initial mutual inclination $\Psi_{m,0}$. The distance of the snow line from the host star is roughly estimated as $a_0 = 2.7(M_s/M_\odot)^2 = 6.24$ AU (i.e. 20 mas). We note that although the position of the snow line is somewhat uncertain, this makes little impact on the following discussions. Then using the conservation relation rewritten as

$$a_0(1 - e_0^2) \cos^2 \Psi_{m,0} = a_n(1 - e_n^2) \cos^2 \Psi_{m,n}, \quad (2)$$

where the indices 0 and n indicate values of the initial state and those as of now, we obtain

$$|\cos \Psi_{m,0}| \leq \sqrt{\frac{0.0386}{6.24} \frac{1}{1 - e_0^2}} |\cos \Psi_{m,n}|, \quad (3)$$

as a necessary initial condition for the orbit of HAT-P-7b. If this condition is satisfied, the eccentricity would be excited over the critical value $\sqrt{1 - 0.0386/6.24} = 0.997$ and the planet would initiate tidal evolution.

We note that the timescale of the Kozai migration under consideration is approximated as (Wu et al. 2007),

$$P_K \sim \frac{M_s}{M_B} \frac{P_B^2}{P_0} (1 - e_B^2)^{3/2}, \quad (4)$$

where M_B , P_B , and e_B are the mass, orbital period, and eccentricity of the binary star, and P_0 is the orbital period of HAT-P-7b at the initial position. Assuming that $M_B = 0.20M_\odot$ (as a typical mass of M star) and $e_B = 0$, we obtain $P_{\text{Kozai}} \sim 300$ Myr, which is sufficiently short relative to the age of this system (~ 2 Gyr). In addition, the timescale of general relativity is estimated as (Wu & Murray 2003),

$$P_{\text{GR}} \sim \frac{2\pi c^2(1 - e_0^2)a_0^{5/2}}{3(GM_s)^{3/2}} \sim 2\text{Gyr}, \quad (5)$$

where c is the speed of light. Thus general relativity would not disturb the Kozai migration of HAT-P-7b at an early stage.

Based on equation (3), if HAT-P-7b was born with $e_0 = 0$ and if $\Psi_{m,n} = 0^\circ$, namely if HAT-P-7b and the binary star are coplanar now, the initial mutual inclination $\Psi_{m,0}$ needs to be within $85.5^\circ - 94.5^\circ$ to initiate the Kozai migration. Even if we assume that the initial eccentricity is large (e.g., $e_0 = 0.8$) and the current mutual inclination is zero, $\Psi_{m,0}$ needs to be within $82.5^\circ - 97.5^\circ$. This is a very optimistic case; if the eccentricity is lower and $\Psi_{m,n}$ is not zero, the required condition becomes more stringent. These required conditions are very tight, but still possible (a few suggestive circumstellar disk observations of nonzero $\Psi_{m,0}$ for young binary stars were reported; e.g., Akeson et al. 1998; Duchêne et al. 2005; Hioki et al. 2009).

4.2. Restricted Area of a Third Body for the Kozai Migration Scenario

As discussed by Wu & Murray (2003) for HD 80606b, a hypothetical additional body HAT-P-7c in the HAT-P-7 system could destroy the Kozai migration process (Innanen et al. 1997), if the timescale of orbital precession of HAT-P-7b caused by the gravitational perturbation from HAT-P-7c ($P_{G,c}$) is shorter than that caused by the Kozai mechanism due to the binary companion ($P_{K,B}$). We calculated a conditional equation for a restricted area of an outer third body at the initial stage as,

$$M_c > \frac{3}{2} M_s \frac{a_c^2 a}{a_B^3} \frac{1}{b_{3/2}^{(1)}}, \quad (6)$$

where a_c and M_c are the semi-major axis and mass of the additional planet, a_B is the semi-major axis of the binary star, and $b_{3/2}^{(1)}$ is the Laplace coefficient (see e.g., Murray & Dermott 2000; Wu & Murray 2003).

The boundary of the restricted area is plotted in figure 3 by solid (for $a_B = 1000$ AU) and dotted (for $a_B = 2000$ AU) lines. The horizontal axis and the vertical axis represent a_c and M_c , respectively. More specifically, the upper region of the solid (dotted) line is the restricted area where HAT-P-7c cannot exist initially for the Kozai migration caused by the binary companion. This constraint is very stringent, and even analogies of Saturn ($a_c = 9.6$ AU, $M_c = 0.3M_{Jup}$) or Uranus ($a_c = 19.2$ AU, $M_c = 0.04M_{Jup}$) cannot exist.

4.3. Impact of HAT-P-7c Reported by Winn et al. (2009)

On the other hand, WJA09 reported that there is indeed a possible third body HAT-P-7c in the HAT-P-7 system (hereafter, just “c”). As a constraint on the mass and semi-major axis of the additional body, WJA09 reported the following equation;

$$\frac{M_c \sin i_c}{a_c} \sim (0.121 \pm 0.014) M_{Jup} \text{ AU}^{-2}, \quad (7)$$

where i_c is the orbital inclination of “c” relative to the line of sight. We plotted equation (7) (assuming $\sin i_c = 0$ for simplicity) in figure 3 using a dashed-dotted line for reference. Obviously, the Kozai migration scenario is totally excluded if “c” existed in the outer region (beyond the snow line) at the initial stage. Thus in the presence of “c”, it is impossible to explain the tilted orbit of HAT-P-7b by the Kozai migration caused by the distant binary companion only.

However, there is another chance of a “sequential” Kozai migration scenario for a 2-body system with a binary star, as introduced by Takeda et al. (2008) and Kita et al. (2010). Namely, an inclined binary companion induces the Kozai mechanism for an outer body first, and then the inclined outer body leads the Kozai mechanism for an inner body. In this case, “c” could play an important role for the migration of HAT-P-7b. If this is the case, “c” could have a tilted orbital axis relative to both the stellar spin axis and the orbital axis of HAT-P-7b. We cannot discuss this possibility in detail at this point, because the orbital parameters of “c” have not yet been determined. If orbital parameters of “c” are firmly determined, it would be interesting to discuss the possibility of a sequential Kozai migration scenario. We also note that if the semi-major axis of “c” turns out to be large, further direct imaging of this inner body would be also interesting in the future (e.g., with TMT or E-ELT).

From the above discussions, we found that the Kozai migration scenario caused by a distant binary star could be realized only in a very limited situation. In addition, if “c” existed, the Kozai migration of HAT-P-7b caused directly by the binary star could not have occurred, although we could not refute the possibility of a sequential Kozai migration for HAT-P-7b at this point. In addition, if neither of the candidate stars is a physical companion of HAT-P-7, only planet-planet scattering can explain the tilted orbit of HAT-P-7b. Thus with a few exceptions above, we conclude that planet-planet scattering is a more plausible explanation for the migration mechanism of HAT-P-7b.

5. Summary

We conducted direct imaging observations of HAT-P-7 with the Subaru HiCIAO and the Calar Alto AstraLux. The system was reported to have the highly tilted transiting planet HAT-P-7b, and massive bodies were expected to exist in the outer region based on planetary migra-

tion theories. We discovered two companion candidates around HAT-P-7. We modeled and constrained the Kozai migration scenario for HAT-P-7b under the existence of a binary star, and found that the Kozai migration scenario was realizable only in a very limited condition and was not favored if the additional body HAT-P-7c existed as reported by WJA09. As a result, we conclude that planet-planet scattering is particularly plausible for the migration mechanism of HAT-P-7b. To complement our conclusion for the migration mechanism of HAT-P-7b, further radial velocity measurements of HAT-P-7 are highly desired to constrain orbital parameters of HAT-P-7c. In addition, further direct imaging and high spectral resolution observations for the candidate companion stars would be very useful to constrain common proper motions and peculiar radial velocities of the stars and thereby to discriminate their binarity.

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